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Entomophagy: A sustainable alternative towards food security

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Abstract

Alternative proteins are mostly sought after because they are more sustainable than conventional protein sources. Prioritizing efforts to create more sustainable alternatives to animal proteins help to address the world's food scarcity and climate change issues. Edible insects in human foods and animal feeds is deemed to play a key role in future sustainable initiatives. In comparison to plant proteins, insect proteins have a higher total protein concentration and good amino acid composition. Due to their substantial levels of high-quality protein and other nutrients, they are considered superior to animal proteins. The market for insect protein is expected to grow significantly between 2022 and 2030, according to various forecasts. In particular, this review explains in detail the most recent developments in the insect protein space. This review assesses the current state of insects as an alternative protein source from production to application and also discusses on associated consumer acceptance. Overall, insect protein products appear to be a good substitute for traditional protein-rich products while lowering greenhouse gas emissions and it can also be a good way to deal with a protein supply deficit. Although, more research studies are needed to further explore its effect on digestibility, product performance, product quality, and health.

Introduction

Food security is becoming an issue for humans due to rapidly increasing population, rising consumption, and a likely decrease in food supplies. The output of agricultural crops has practically plateaued, and hunger is rife in many developing countries. Food insecurity appears to be caused by natural factors such as climate change, energy crisis, decreasing soil fertility, the incidence of pests and plant diseases, and man-made situations such as increased food prices, non-availability of foods, lack of purchasing power of consumers, and disparity in food distribution (Bao and Song 2022; Dopelt, Radon, and Davidovitch 2019). The global food demand is expected to rise for the next 40 years. Additionally, the global population is expected to surpass 9.8 billion by 2050 (Mafu et al., 2022). Alternatively, global meat consumption is anticipated to increase by 75%, where approximately 465 million tons of meat will be consumed annually by 2050 (Sakadevan and Nguyen 2017, Imathiu 2020). However, the meat industry poses a growing threat to the environment such as climate change resulting from greenhouse gas emissions (GHG), deforestation, loss of plant biodiversity, and water pollution (Dopelt, Radon, and Davidovitch 2019, Huis and Oonincx 2017). If this alarming situation continues for an extended period, people will become food insecure (Bao and Song 2022). New technologies to improve food supply, such as genetically modified crops, geo-engineering, crop genotypes resistant to pests, diseases, and drought, integrated plant nutrients, and pest management, etc., may take time to apply on a large scale to make them feasible/practical, cost-effective, and eco-friendly. Hence, it is crucial to identify alternative food protein sources for the future of a sustainable and secure food supply. The Food and Agriculture Organization (FAO) of the United Nations took the initiative to develop a policy and proposed a new program to feed people with other sources, such as insects (Naseem et al. 2021).

Even without food security challenges, many experts believe the current ecological footprint of the global food system which includes its production as well as consumption is unsustainable. Cattle production for meat and dairy products is particularly problematic because of the burden it places on land and other vital resources (Glover and Sexton, 2015). The key to a sustainable economy is the high production of protein and other high-quality food sources at low input costs. The conventional method of producing meat is quite inefficient from a sustainability perspective or new methods may have to be introduced to make it more eco-friendly. Cattles are responsible for 77% of the total area used for farming around the world, but they only produce 18% of the world's calories when grazing pastures and the land that is required to grow feed for livestock are taken into account. Water is another major consideration when discussing the ecological footprint of food sources. Some estimates suggest that livestock and agricultural practices utilize nearly 70% of the total water consumed in the United States (United Nations FAO 2017; Doreau et al. 2012). While livestock feed production uses the most water, water pollution generated through the livestock sector has serious repercussions as well. In the U.S., livestock creates 55% of freshwater erosion, 37% pesticide pollution, and 50% antibiotic pollution (Bao and Song 2022). Additionally, GHG emissions from livestock production which includes the transport of cattle and feed represent roughly 18% of global human-caused GHG emissions (Huis 2012). Methane (CH_4) is produced by enteric fermentation, which accounts for 31% of global emissions; nitrous oxide (N_2O) is released mostly through feed crop fertilizer and manure, which accounts for 65% of total emissions. Several studies have reported that the environmental impact of one kilogram of beef is the largest when evaluated in CO_2 equivalents (14.8 kg), followed by that of one kilogram of pork (3.8 kg), and then that of one kilogram of chicken (1.1 kg) (Huis 2012). The feed conversion ratio (FCR) for conventional meat sources is also relatively higher. The importance of FCRs is exacerbated by the fact that an increase in the demand for meat will result in an increased demand for grain and high-protein feeds. The FCRs per kilogram of feed input are as follows: pork (5), chicken (2.5), and beef (10) (Naseem et al. 2021).

The environmental benefits of insect farming are decreased land use, lowered water consumption, fewer GHG emissions, and high feed conversion efficiency. Mealworms, a commonly consumed insect, utilize far less land than chicken (130 to 185% more), pork (157 to 249% more), and beef (689 to 1312% more) (Oonincx and Boer 2012). Similarly, insect production uses significantly less water than conventional livestock. Insects require 56 times less water per gram of protein than beef, 28.5 times less water than pork, and 17 times less water than chicken (Bao and Song 2022). As for GHG emissions, 1 kilogram of edible insects produces up to 100 times fewer GHSs than the same amount of meat from ruminants such as beef (Bao and Song 2022). Moreover, insects would produce far smaller effluent flows than cattle mammals, which are a significant source of pollution from intensive feedlots (Glover and Sexton 2015). Regarding FCR, studies suggest that the FCR efficiency of crickets is greater than traditional meat sources. For example, Cricket's FCR is 10 times more than beef (Naseem et al. 2021; Huis 2012).

While nutritional composition varies by insect species, data from 236 edible insect species showed that they sufficiently meet humans' needs for energy, protein, amino acids, lipids, and several minerals and vitamins. Insects contain a high iron and zinc content compared to ruminant meats, which can help improve malnutrition in developing countries, which have high zinc and iron deficiencies. Food loss is another major attribute when livestock animals are compared to insects. It is important to note that studies have reported that the average edible portion of insects such as crickets can be as high as 80% when compared to other meat sources such as pork (55%), chicken (58%), and beef (40%) (Naseem et al. 2021; Bao and Song 2022; Nakagaki and Defoliart 1991). Similarly, the availability of protein per kilogram can also be compared between livestock animals and insects. Cricket nymphs and adults have 154 and 205 g of protein per kilogram edible weight, compared to 200, 150, and 190 for poultry, pork, and beef, respectively (Huis 2012). In all situations, the use of insects as a food source which is referred to as entomophagy is unquestionably the most practical, sustainable, sophisticated, and feasible means of meeting energy needs. The aim of this review is to provide a summary of the use of insects as food which includes their production and processing as well various forms of consumption. The review also provides insight into some of the regulations as well as consumer acceptance.

Entomophagy: Advantages

Entomophagy is the term for the activity of consuming insects as food. At least 400 million years have passed since insects first appeared, placing them among the earliest land animals. Insects form as much as 80% of the animal kingdom and are the largest animal class on earth. Due to the nutritious value and vast availability of edible insects, more than two billion people consume them every day. Various researchers have documented more than 1900 species of edible insects in 300 ethnic groups across 113 countries (Bernard and Womeni 2017). According to Huis et al. 2013, 246 edible insect species have been documented in 27 African nations. And another study indicates Africa being the largest resource of edible insect biodiversity with 524 species recorded from 34 African nations (Ramos-Elorduy 2005). **Table 1** provides information regarding the most consumed edible insects and their order. At present, approximately 2.5 billion people globally use more than 1900 insect species as a fundamental part of their diets (Huis 2016). As reported by studies (DeFoliart 1992, Ramos-Elorduy 2009), the initial consumption of insects by human beings was reported around 7000 years ago. Entomophagy offers several benefits as a food source. Insects can be harvested in a shorter amount of time whenever their populations are abundant in forestland and water resources. As a result of their short life cycle and rapid intrinsic growth rate, insects can be easily grown and replicated in small locations over a short time span. Since edible insects do not need to be fed grains, their raising is more eco-friendly than conventional livestock (Oonincx et al., 2010). Furthermore, the Efficiency of Conversion of Ingested food (ECI) is greater (up to 44% in certain insects) than in conventional meats. The ECI of the house cricket is twice as efficient as that of pigs and broiler chickens, four times that of sheep, and six times that of a steer when carcass trim losses and dressing percentage are factored in. (Capinera 2008).

Order	Species	Most common insects	Percentage
Lepidoptera	*Anaphe panda* (Boisduval) *Cirina forda* (Westwood) *Dactyloceras lucina* (Drury) *Gynanisa ata* Strand *Anaphe venata* Butler	Butterflies and moths Mostly consumed as Caterpillars	17.79
Coleoptera	*Oryctes boas* (Fabricius) *Rhynchophorus phoenicis* (Fabricius)	Beetles	32.38
Hymenoptera	*Apis mellifera* (Linnaeus) *Carebara vidua* (Smith) *Carebara lignata* Westwood	Bees, wasps, and ants	15.77
Orthoptera	*Acanthacris ruficornis* (Fabricius *Ruspolia differens* (Serville) *Zonocerus variegatus* Linnaeus)	Grasshoppers, locusts and Crickets	13.66
Hemiptera	*Cosmopsaltria waine* (Duffels) *Pomponia merula* (Distant)	Cicadas, leafhoppers, planthoppers, scale insects, and true bugs	11.65
Isoptera	*Macrotermes subhyalinus* (Rambur) *Macrotermes falciger* (Gerstäcker) *Macrotermes natalensis* (Haviland)	Termites	2.99
Diptera	*Chaoborus edulis*	Flies	1.82

Table 1: Edible Insects order, species, and their % consumption by humans (Naseem et al. 2021; Bernard and Womeni 2017; Banjo, Lawal, and Songonuga 2006; Igwe, Cosmas, and Nwaogu 2012; Opara et al. 2012; Kelemu et al. 2015).

Insects as food

The market for edible insects is expected to increase to 1.2 billion globally by 2023 (Liceaga., 2021). Some of the most popular insects that have been raised for food and feed include crickets like *Acheta domesticus* (L.), *G. bimaculatus De Geer*, *Gryllus assimilis* (Fab.), *Gryllodes sigillatus* (Walker), and *G. locorojo* Weissman and Gray; the greater wax moth, *Galleria mellonella* L.; mealworms like *Zophobas atratus* Fab., *Tenebrio molitor* L., *Z. morio* Fab., and *Alphitobius diaperinus* Panzer; the housefly, *Musca domestica* L.; and the black soldier fly, *Hermetia illucens* (L.) (Cortes and Ruiz. 2016). Insects have a highly variable protein content that ranges from 7.5% to 91%, with many species having over 60% protein on a dry matter basis (Oonincx and Dierenfeld, 2012). Insects' fat content varies from 10 to 60% on a dry matter basis depending on the species, season, reproduction stage, sex, habitat, and diet (Schlüter et al., 2017). Insect protein is typically considered to have good nutritional value, although the quality relies on how easily the amino acids can be digested and how well the amino acid profile fits the needs of the insectivore (Finke and Oonincx, 2023). Common food products made with insects are insect flour (pulverized, freeze-dried insects), insect burger (patties made from insect flour), insect fitness bars (protein bars made from insect powder, insect pasta (pasta made of wheat flour, fortified with insect flour, insect bread (bread made with insect flour (mostly house crickets), insect snacks (crisps and snack bites). Insect rearing for entomophagy appears to fit neatly with a contemporary food production system due to the great resource efficiency and good nutritional content of insects.

Production and processing of insect protein

The market for edible insects is expanding at an astounding rate, and there is an increasing need for new or novel foods and ingredients (Van Thielen et al., 2018; Melgar-Lalanne et al., 2019). Blanching can be applied as a pretreatment to the majority of commercially available edible insects in order to lower microbial counts and inactivate the degradative enzymes that cause food spoilage and poisoning. For each insect species, a customized blanching technique should be developed to maximize antimicrobial effects with the least amount of quality loss (Melgar-Lalanne et al., 2019). Blanching should lower the microbiological dangers related to eating edible insects, and it could be used with methods that can lessen the amount of bacterial spores' present (Caparros Megido et al., 2017). Insect flours and powders are often dried using freeze-drying, oven-drying, or non-conventional methods, whereas whole edible insects are best dried using sun drying, freeze-drying, and oven-drying technology. One of the chosen technologies for boosting human consumption of insects, primarily in Western nations, is drying and grinding whole insects into powders (Menozzi et al., 2017). Drying also extends the shelf life of the product during distribution and storage. Smoking is a thermal and curing process that could be employed in insect processing. For insects, smoking is done in a dry environment, and curing is done at the same time as drying (Tiencheu et al., 2013). Furthermore, efficient processing methods could improve the aroma, texture, color, taste, and other sensory qualities of insect protein according to the current market demands (Mishyna, Chen, & Benjamin, 2020). Research on processing techniques that produce optimal protein yields and purity balance is still limited and is typically only tested at lab scale. Future research should concentrate on determining the best processing conditions to create insect protein isolates with good functional characteristics, cost-effectiveness, and environmental sustainability that can be used in food formulation (Gravel & Doyen, 2020). According to Williams et al. (2016), processing insects can increase their quality, safety, flavor, and shelf life, but it can also occasionally result in the development of anti-nutritional and/or poisonous components. Additionally, depending on the insect species, several studies investigated how processing affected the nutritional makeup and bioavailability of nutrients in edible insects. For toasted and dried grasshoppers, protein digestibility was significantly reduced according to Kinyuru et al. (2010), whereas for toasted and dried termites, there was no discernible difference. On the other hand, Megido et al. (2018) found that cooking mealworms in the oven or boiling water significantly increased their ability to digest protein.

Regulations and consumer acceptance

Insect consumption is widespread around the world and is frequently seen as a delicacy in parts of Latin America, Asia, and Africa where it is thought to be an important source of nutrition for the local populations (Raheem et al., 2019). In many parts of the world, people regularly eat insects as food, and entomophagy is strongly impacted by cultural and religious traditions. However, entomophagy is generally despised and associated with barbaric behavior in the majority of Western nations. Nevertheless, it is estimated that at least 2 billion people consume insects on a regular basis worldwide, from consuming ants to beetle larvae as part of their subsistence diets in tribes in Africa and Australia to enjoying crispy-fried locusts and beetles in Thailand. According to a survey on edible insects in Thailand (Bangkok), 164 species of insects are accepted positively by consumers as a part of their food (Naseem et al., 2021; Yhoung-Aree, 2010). Another investigation by Feng et al. (2018) on edible insects reported about 324 distinct kinds of insects being sold and eaten by consumers in China. Studies have also emphasized the significance of insects in the diet of particular African cultures. Grasshoppers provide roughly 16,100 Kcal of protein per person per year in Uganda, whereas in the Democratic Republic of the Congo, caterpillars alone account for 40% of all the animal protein consumed, and in the case of Zimbabwe, only less than 10% of the population does not consume insects (Mutungi et al., 2019). Entomophagy is still in its early stages in Europe and Australia. A study by Lensvelt and Steenbekkers (2014) investigated the acceptance of entomophagy on the Dutch and Australian consumers and reported the consumer acceptability to be influenced by seven variables; price, quality, benefits naturalness, risks, trust, fit with consumer needs , and attitude/culture. Currently, a variety of models are employed to forecast consumer purchasing behavior. The Theory of Planned Behavior is one of the consumer behavior models that may be used to forecast whether consumers would adopt symbiotic items. The Theory of Planned Action (TPB) makes predictions about a person's intention to engage in a behavior at a particular time and place. The most common method for determining acceptability to entomophagy in the West has been to use measures of reported "intent" or "willingness." These have included a willingness to: consume/try insects in various forms (Woolf, Zhu, Emory, Zhao, & Liu, 2019); paying for insect-based products (Lombardi, Vecchio, Borrello, Caracciolo, & Cembalo, 2019); purchase insect-based foods (Piha, Pohjanheimo, Lähteenmäki-Uutela, Křečková, & Otterbring, 2018); and substitute insects for meat (Megido et al., 2016). Due to cultural and customary restrictions, many people were first hesitant to accept insects as food. However, because to its novelty and cutting-edge processing methods, customer attitudes regarding its acceptance have shifted in more recent years. This attitude now influences human eating behavior, including food preferences and choices (Alley, 2018).

People have historically been more at ease with insects' existence in the food chain in continents like Africa and Asia, but this is not reflected in law, as standards and regulations that acknowledge the use of insects as food and feed ingredients are rare on both the national and international levels. While local manufacturers of insect-related goods might easily sell their wares in their domestic markets, exports to industrialized nations may be difficult in the absence of a defined legal framework. Eating habits in recent years have undergone a significant change as a result of globalization and rising consumer awareness over food quality. As a result, in the last 20 years, the regulatory frameworks governing food and feed have significantly evolved and increasing emphasis has been given to food safety and the quality of traded food items. The Ministry of Public Health is currently the main organization in charge of overseeing insect production and consumption in Thailand. Thailand has a significant and lucrative commercial insect industry that mostly serves human consumption. The Thai Food and Drug Administration (FDA), a part of the Ministry of Public Health, must first legally approve any insectderived products before they can be sold domestically or abroad. Since there are no specific rules for edible insects, the Food Act of B.E. 2522 states that they must be treated like any other food product (Halloran, Flore, Vantomme, & Roos, 2018). There aren't many policies or regulations in China that prohibit eating insects as food, and the national Food and Drug Administration hasn't yet adopted any guidelines or regulations that control edible insects on a national level. Bee pollen, ants, and insect protein are just a few of the insect-based meals that fall under the Chinese novel food rule, which came into effect in 2007 (Lahteenmaki-Uutela et al., 2017). In the US, edible insects are regarded as food additives. According to the Federal Food, Drug, and Cosmetic Act, a substance is a food additive if its intended use results in or may reasonably be expected to result in the substance becoming a component or otherwise affecting the characteristics of any food, and unless its use is Generally Regarded As Safe (GRAS) or otherwise exempted from the classification of a food additive (FAO, 2014). By Regulation 2015/2283EC, insects are recognized as novel foods in Europe. This regulation was approved in November of 2015 and implemented in January 2018 have established a centralized authorization process and an assessment method for insect foods (EFSA), 2016). However, as Regulation 2015/2283EC includes a proof of the history of safety for traditional food from a third nation, as well as any insect used as food within the EU prior to 15 May 1997, these standards for novel foods require updating. Moreover, currently there are no guidelines for those foods composed of insects under the EU's standards on food hygiene (852/2004), foods of animal origin (853/2004), or the microbiological requirements (2073/2005) (Lahteenmaki-Uutela et al., 2017). In Canada, three tiers of government—federal, provincial, and municipal—share regulatory authority over insects for use as food. For food that is imported, exported, or novel, the federal government is in charge through Health Canada. Agriculture and food processing are regulated by provincial governments, and each province may have its own set of regulations. According to the Canadian Food and Drug Act, insects meet the statutory definition of food and prior to entering the Canadian market, novel foods are evaluated for its safety and nutritional adequacy. The Food Directorate of Health Canada's Novel Foods Section Bureau of Microbial Hazards, in collaboration with the Bureau of Chemical Safety and the Bureau of Nutritional Sciences, is responsible for this evaluation (FoodandDrugRegulations., 1985). Whereas in Mexico, several gathered insects are regulated and marketed under the article 144 of organic food law (Lahteenmaki-Uutela et al., 2017).

Challenges and future direction

One of the main obstacles to insect-containing food products is still very much associated with consumer acceptance (Jensen & Lieberoth, 2019). In fact, most customers are repulsed by the prospect of eating insects, even though they are advertised as a delicacy in restaurants in several countries, notably Western entomophagy-disgust from an insect tasting still persists. Main obstacles to eating insects have been identified by a few research to better understand this phenomenon of food aversion (La Barbera et al., 2018; Gere et al., 2017). These studies indicated that less aversion was noticed by insect-based foods where the insects could not be seen by the consumer, underscoring the significance of creating products containing processed insects. Overall, the majority of research concurred that Western consumers were not yet ready to try eating foods with insect-based ingredients and were even much less inclined to consider doing so on a daily basis (Verbeke, 2015). The allergenicity of edible insects is another problem that needs to be addressed. In fact, cross-allergic responses to proteins in crustaceans and house dust mites have been linked to insects. Indeed, people who are sensitive to house dust mites and/or crustaceans are more likely to also be allergic to edible insects (Ribeiro et al., 2018). Insects may nevertheless serve as contamination vectors depending on their raising environment, such as if the insects came into contact with *Salmonella* or *Campylobacter*. Osimani et al. (2018) noted bread enriched with cricket flour contained spore-forming microorganisms. According to the European Food Safety Authority, heavy metals including cadmium, mercury, lead, and arsenic as well as accumulated pollutants from the environment such as hormones and pesticides are the chemical contaminants that are most concerning. Furthermore, several mycotoxins have been found in edible insects, and mycotoxins like aflatoxins are known to cause cancer, and are the most dangerous (Musundire et al., 2016). Dagevos (2021) noted that studies from 2019 demonstrated that, in terms of consumer studies, insect sustainability and circularity gains are still in their infancy.

One key strategy for sustainability and fostering global food security is to substitute alternative protein sources for animal proteins or to create hybrid products. The creation of marketable insect-based food products is deemed a feasible option. Due to their potential as an effective, sustainable, and secure supply of nutrients, insect protein-based products have attracted growing attention in recent years. The food industry is currently investigating ways to include insects in well-known foods, producing goods that are identical in appearance and flavor to more traditional food items. Insects are employed as ingredients in various products, typically by turning them into flour. These insect-based ingredients provide a good substitute, especially for environmentally conscious consumers who are drawn to this novel meal but repulsed by the thought of eating visible insects. However, there are several issues that must be resolved before using edible insects to improve food security. Although most funding is currently going toward using insects as food for other animals, in order to establish the foundation for promoting insects as a nutritious food source for humans, it is important to further explore the nutritional content and health advantages of various insects. Although Western customers aren't quite ready for whole insects, they aren't against advances and food innovations. Additionally, many communication strategies are needed to encourage consuming insects. Advancements in insect raising, transportation, processing, and exploring more ways of its inclusion in feed and food, will make the insect value chain more competitive not just in a few countries but also internationally and open new market opportunities.

Conclusion

In the quest for food security, entomophagy is a viable, sustainable, inexpensive, and extremely nutritious approach. Entomophagy can be revalidated by launching global campaigns in countries experiencing an acute food scarcity. Developed and developing nations should work together to popularize entomophagy through joint, focused efforts. Extensive insect surveys, literature searches, studies on the nutritional worth of unknown species, as well as socioeconomic factors (consumer acceptance of these foods) might open up new avenues for food security. Despite all current efforts, there are still some gaps that prevent adoption of entomophagy from being fully functional. They have the potential to be more useful and efficient if certain cultural barriers are overcome, and if appropriate information is disseminated regarding them. Finally, a thorough and unambiguous legal framework is required at both the international and national levels to open the way for additional investment, which will ultimately lead to the full growth of production and international trade in insect products as sources of food and feed.

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